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Top Production in Hadron–Hadron Collisions and Anomalous Top–Gluon Couplings

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Abstract:

We discuss the influence of anomalous $t\bar{t}G$ couplings on total and differential $t\bar{t}$ production cross sections in hadron–hadron collisions. We study in detail the effects of a chromoelectric and a chromomagnetic dipole moment, d_t' and μ_t', of the top quark. In the d_t'–μ_t' plane, we find a whole region where the anomalous couplings give a zero net contribution to the total top production rate. In differential cross sections, the anomalous moments have to be quite sizable to give measurable effects. We estimate the values of d_t' and μ_t' which are allowed by the present Tevatron experimental results on top production. A chromoelectric dipole moment of the top violates CP invariance. We discuss a simple CP–odd observable which allows for a direct search for CP violation in top production.

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1 Introduction

The observation of the top quark has recently been reported by both experimental groups, CDF and D0, working at the Tevatron $p\bar{p}$ collider. The latest CDF value for the top quark mass is $m_t = 176 \pm 8 \pm 10$ GeV [1], while D0 gives the value of $m_t = 199^{+19}_{-21} \pm 22$ GeV [2]. At the Tevatron, top quarks are pair produced in $p\bar{p}$ collisions at a c.m. energy of $\sqrt{s} = 1.8$ TeV. Based on an integrated luminosity of 67 pb^{-1}, the CDF result for the total cross section for this reaction is found to be [1]

$$\sigma_{\rm exp}(p\bar{p} \to t\bar{t}X) = 6.8^{+3.6}_{-2.4} \text{ pb} . \tag{1}$$

The D0 collaboration obtains from a data sample corresponding to 50 pb^{-1} the cross section [2]

$$\sigma_{\rm exp}(p\bar{p} \to t\bar{t}X) = 6.4 \pm 2.2 \text{ pb} . \tag{2}$$

Both central values are higher than the best theoretical prediction [3]

$$\sigma_{\rm th}(p\bar{p} \to t\bar{t}X) = 4.79^{+0.67}_{-0.41} \text{ pb} \quad \text{for} \quad m_t = 176 \text{ GeV} , \tag{3}$$

obtained from a $\mathcal{O}(\alpha_s^3)$ Standard Model (SM) calculation including a resummation of the leading soft gluon corrections to all orders of perturbation theory. The electroweak corrections are known to be small, of the order of a few percent [4]. For higher values of m_t, the theoretical cross section is even lower. Taking the values in Eqs. (1)–(3) literally we obtain for a possible anomalous contribution to the cross section

$$\begin{aligned} \Delta\sigma_{\rm exp} &\leq \sigma_{\rm exp}^{\rm mean} - \sigma_{\rm th} + \sqrt{(\delta\sigma_{\rm exp}^{\rm mean})^2 + (\delta\sigma_{\rm th})^2} \\ &\simeq 1.8^{+2.9}_{-2.4} \text{ pb} . \end{aligned} \tag{4}$$

Thus the presently available experimental and theoretical information allows a rather large anomalous contribution.

Future experimental runs will increase the number of produced $t\bar{t}$ pairs, allowing the comparison of differential cross sections with theory [5–7]. One will be able to investigate also many other observables, e.g. CP–odd ones. From these measurements one expects to obtain detailed information on the couplings of the top quark. This might provide a further confirmation of the Standard Model or open a window to new physics.

Of special interest is the study of CP–odd observables in top production and other channels of $p\bar{p}$ collisions [8–14]. For theoretical investigations of CP violation in top production and decay in other contexts we refer to [15–29] and references therein.

In this paper we want to investigate possible effects of anomalous top–gluon couplings on total and differential cross sections of the reaction $p\bar{p} \to t\bar{t}X$. To be specific, we assume the existence of chromoelectric and chromomagnetic top

dipole moments, d_t' and μ_t'. Although there are stringent experimental bounds on anomalous contributions to dipole moments of light fermions, it is not unreasonable to expect large anomalous moments for the heavy top quark. One way to generate these couplings is the exchange of Higgs scalars in one–loop diagrams in multi–Higgs extensions of the SM. Since the top–Higgs coupling is proportional to m_t, the effective dipole coupling can be quite sizable.

In principle, the anomalous couplings d_t' and μ_t' should be considered as formfactors, depending on the kinematic variables of the reaction. However, in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV the $t\bar{t}$ pairs are produced near threshold, where constant formfactors should be a good approximation. Another way to put it is to consider in the framework of effective Lagrangians an expansion in new coupling terms, ordered by their dimension. The expansion parameter is then $1/\Lambda$, with Λ the scale of new physics. The dipole moments d_t' and μ_t' correspond to the dimension 5 terms (after symmetry breaking [17]), i.e. the terms of order $1/\Lambda$, in the effective Lagrangian.

Some effects of the top dipole moments d_t' and μ_t' in the reaction

$$p\bar{p} \longrightarrow t\bar{t}X \tag{5}$$

have been investigated previously. In [11], the contribution of both electric and magnetic moments to the matrix element of the parton reactions underlying (5), including final quark polarisation, was calculated, but only to first order in the anomalous couplings. The quark spin vectors were then used for the construction of a CP–odd observable. In Ref. [12] the contribution of d_t' to various CP–odd observables was studied. In Ref. [14], total and differential cross sections were computed up to fourth order in μ_t', but for vanishing d_t'.

In the following we want to extend the above analyses and investigate the combined effects of d_t' and μ_t' simultaneously. The outline of our calculation is as follows: We will set the light quark masses to zero and compute the parton processes $q\bar{q} \to t\bar{t}$ and $GG \to t\bar{t}$ to leading order (LO) in QCD, i.e. at tree level, but including the effects of d_t' and μ_t'. Convoluting the parton level results with the parton distribution functions, we evaluate the cross section for $p\bar{p} \to t\bar{t}X$ which depends now, of course, on d_t' and μ_t': $\sigma(d_t', \mu_t')$. We identify the anomalous cross section (calculated to LO) as

$$\Delta\sigma := \sigma(d_t', \mu_t') - \sigma(0, 0) \; . \tag{6}$$

We then add $\Delta\sigma$ to the best next to leading order (NLO) SM calculation available [6]. We note here that higher order QCD effects produce, of course, a chromomagnetic moment form factor. These effects are included in the NLO SM calculation and do not concern us here. Our anomalous moment μ_t' is understood as the additional piece in the chromomagnetic moment form factor which may be there due to new couplings. Similarly, higher order electroweak corrections in the SM will produce a chromoelectric dipole form factor, which, however, is estimated to be unmeasurably small. Thus, a sizable chromoelectric dipole form factor must come from physics beyond the SM.

In [6] it was shown that single top differential cross sections from the full NLO calculation in the SM can well be approximated by a multiplication of the LO Standard Model result with a constant factor between 1.4 and 1.6. Such a constant factor drops out in normalized differential distributions. Thus the effects of new couplings in differential distributions calculated in LO as described below can hardly be masked by NLO SM effects. Finally we discuss the sensitivity of a simple CP–odd observable from [12] to the chromoelectric dipole moment d_t'.

2 The model

We work with the following effective top–gluon interaction Lagrangian:

$$\mathcal{L}_{t\bar{t}G} = -g_s\,\bar{t}\gamma^\mu G_\mu t - i\frac{d_t'}{2}\,\bar{t}\sigma^{\mu\nu}\gamma_5 G_{\mu\nu} t - \frac{\mu_t'}{2}\,\bar{t}\sigma^{\mu\nu} G_{\mu\nu} t\ . \tag{7}$$

Here g_s is the strong coupling constant, μ_t' and d_t' are the chromomagnetic and chromoelectric dipole moments, $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$, $G_\mu = G_\mu^a T^a$ with the gluon fields G_μ^a and the $SU(3)_C$ generators $T^a = \frac{1}{2}\lambda^a$ (a=1...8), and $G_{\mu\nu} = G_{\mu\nu}^a T^a$ with the gluon field strength tensors $G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c$. Since the anomalous operators have mass dimension 5, we introduce the dimensionless dipole moments $\hat{d}_t'$, $\hat{\mu}_t'$ via

$$d_t' = \frac{g_s}{m_t}\hat{d}_t'\ , \qquad \mu_t' = \frac{g_s}{m_t}\hat{\mu}_t'\ , \tag{8}$$

with the top mass m_t. Both anomalous dipole moment couplings are chirality changing; the magnetic moment term is even under the combined action of charge and parity transformations CP, while the electric moment is CP–odd. The signs and factors of $\frac{1}{2}$ are chosen such as to yield the correct nonrelativistic limits. In Fig. 1 we show the Feynman vertex factors following from Eq. (7); note in particular that due to gauge invariance there is also a $t\bar{t}GG$ coupling. For the coupling of light quarks q to gluons as well as for the gluon self coupling we take the SM values.

With this input we calculate the differential cross sections $\hat{\sigma}_{q\bar{q}}$ and $\hat{\sigma}_{GG}$ for the parton level processes

$$\begin{aligned} q(q_1)\ +\ \bar{q}(q_2)\ &\longrightarrow\ t(k_1)\ +\ \bar{t}(k_2)\ , \\ G(q_1)\ +\ G(q_2)\ &\longrightarrow\ t(k_1)\ +\ \bar{t}(k_2)\ , \end{aligned} \tag{9}$$

to lowest order in QCD, as a function of the usual Mandelstam variables

$$\hat{s} = (q_1+q_2)^2\ , \quad \hat{t} = (q_1-k_1)^2\ , \quad \hat{u} = (q_1-k_2)^2\ . \tag{10}$$

For the quark annihilation, there is only the $\hat{s}$-channel diagram shown in Fig. 2a (the corresponding $\hat{t}$- and $\hat{u}$-channel diagrams are absent, since we set the top distribution in the proton and antiproton to zero). The result has the form

$$\frac{d\hat{\sigma}_{q\bar{q}}}{d\hat{t}} = \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{8}{9}\left(\frac{1}{2} - v + z + 2\hat{\mu}_t' + (\hat{\mu}_t'^2 - \hat{d}_t'^2) + (\hat{\mu}_t'^2 + \hat{d}_t'^2)\frac{v}{z}\right)\ , \tag{11}$$

where we used the abbreviations

$$z = \frac{m_t^2}{\hat{s}} , \qquad v = \frac{1}{\hat{s}^2}(\hat{t} - m_t^2)(\hat{u} - m_t^2) \tag{12}$$

with the kinematical limits $0 \le z \le \frac{1}{4}$, $z \le v \le \frac{1}{4}$. The variable v can be expressed in terms of the emission angle $\hat{\vartheta}$ of the top quark in the parton c.m. system as

$$v = \frac{1}{4}(1 - r^2 \cos^2 \hat{\vartheta}) , \qquad r = \sqrt{1 - 4z} . \tag{13}$$

For the gluon fusion process we have to consider the four diagrams in Fig. 2b–e, and we find

$$\begin{aligned} \frac{d\hat{\sigma}_{GG}}{d\hat{t}} &= \frac{\pi\alpha_s^2}{\hat{s}^2}\frac{1}{12}\Big[\left(\frac{4}{v} - 9\right)\left(\frac{1}{2} - v + 2z(1 - \frac{z}{v}) + 2\hat{\mu}_t'(1 + \hat{\mu}_t')\right) \\ &+ (\hat{\mu}_t'^2 + \hat{d}_t'^2)\left(\frac{7}{z}(1 + 2\hat{\mu}_t') + \frac{1}{2v}(1 - 5\hat{\mu}_t')\right) + (\hat{\mu}_t'^2 + \hat{d}_t'^2)^2\left(-\frac{1}{z} + \frac{1}{v} + \frac{4v}{z^2}\right)\Big] . \end{aligned} \tag{14}$$

In the limit $\hat{d}_t' = \hat{\mu}_t' = 0$, we recover the well known SM results [30]. We also checked against Ref. [14] for the case $\hat{d}_t' = 0$, where we disagree partly[1]. At Tevatron energies, tops are produced predominantly via the annihilation of quarks; the gluon fusion process becomes important for increasing energy as well as for higher values of the anomalous dipole moments.

According to the parton model, the cross section for the reaction $p\bar{p} \to t\bar{t}X$ is obtained from a convolution of the subprocesses Eq. (9) with parton distribution functions,

$$\begin{aligned} &d\sigma\Big(p(p_1) + \bar{p}(p_2) \to t(k_1) + \bar{t}(k_2) + X(k_X)\Big) = \\ &= \sum_a \int_0^1 dx_1 \int_0^1 dx_2 \; N_a^p(x_1) N_{\bar{a}}^{\bar{p}}(x_2) d\hat{\sigma}_{a\bar{a}}\Big(a(x_1 p_1) + \bar{a}(x_2 p_2) \to t(k_1) + \bar{t}(k_2)\Big) , \end{aligned} \tag{15}$$

where the sum runs over all light quark flavors and the gluons, $a = u,\bar{u},d,\bar{d},c,\bar{c},s,\bar{s}$, $b,\bar{b},G$. We evaluate the distribution functions $N(x,s)$ at the hadron c.m. energy $\sqrt{s}$, whereas the energy $\sqrt{\hat{s}}$ of the parton subprocess sets the scale for α_s. In particular, the total cross section can be written as

$$\sigma(s) = \sum_a \int_0^1 dx_1 \int_0^1 dx_2 \; N_a^p(x_1) N_{\bar{a}}^{\bar{p}}(x_2) \; \Theta(x_1 x_2 s - 4m_t^2) \hat{\sigma}_{a\bar{a}}(\hat{s} = x_1 x_2 s) . \tag{16}$$

The total parton level cross sections, $\hat{\sigma}_{q\bar{q}}$ and $\hat{\sigma}_{GG}$, can be calculated analytically and we include the result for completeness in Appendix A.

[1] Apparently there are some misprints in the formulae of [14]. In Eq. (2) (quark annihilation) there is a factor of β^2 missing in the last term, as well as an overall factor of 4. In Eq. (6) (gluon fusion) we agree with the terms T_1–T_4, but not with the SM contribution T_0 (in the second factor there is a term $32x^2$ missing). Note also that κ defined in [14] is related to our $\hat{\mu}_t'$ by $\kappa = 2\hat{\mu}_t'$.

Finally we give a useful form of the double differential cross section with respect to rapidity y and transverse energy E_T of the t jet,

$$\frac{d^2\sigma}{dy\, dE_T} = 2\sqrt{s}\Delta \sum_a \int_0^1 d\tau\ N_a^p(x_1(\tau)) N_{\bar{a}}^{\bar{p}}(x_2(\tau))\ \frac{d\hat{\sigma}_{a\bar{a}}}{d\hat{t}}\ , \tag{17}$$

with

$$\Delta = \frac{\sqrt{s}}{E_T} - 2\mathrm{cosh}y\ , \quad x_1(\tau) = \frac{1}{1+\tau\Delta \mathrm{e}^{-y}}\ , \quad x_2(\tau) = \frac{1}{1+(1-\tau)\Delta \mathrm{e}^{y}}\ , \tag{18}$$

and the kinematical limits $m_t \le E_T \le \sqrt{s}/(2\mathrm{cosh}y)$. In $d\hat{\sigma}_{a\bar{a}}/d\hat{t}$ one has to perform the substitutions $\hat{s} \to x_1(\tau)x_2(\tau)s$ and $z \to E_T^2/(x_1(\tau)x_2(\tau)s)$. This completes our presentation of the formulae we need.

3 Results

The numerical evaluation was carried out for the Tevatron, i.e. we consider $p\bar{p}$ collisions at a c.m. energy of $\sqrt{s} = 1.8$ TeV. For the top mass we took 175 GeV. We used various parton distribution functions (PDF) from the CERN library PDFLIB, but found only weak dependence on the actual set; the presented results were computed with the set HO of Glück, Reya and Vogt [31].

In Fig. 3 we show a contour plot of the anomalous contribution $\Delta\sigma$ defined in Eq. (6) in the $\hat{d}_t'$–$\hat{\mu}_t'$ plane. This quantity has a minimal value of

$$\Delta\sigma_{\mathrm{min}} = -2.10 \qquad \text{for} \quad \hat{d}_t' = 0\,, \ \ \hat{\mu}_t' = -0.4 \tag{19}$$

and increases roughly quadratically with $\hat{d}_t'$, $|\hat{\mu}_t' + 0.4|$. We therefore find a whole region where the contributions of $\hat{d}_t'$ and $\hat{\mu}_t'$ cancel. The dashed lines include the experimentally allowed region (cf. Eq. (4)). Along the solid (dotted) line $\Delta\sigma$ takes the value 1.8 pb (0.0 pb). As explained before, the anomalous contribution has to be added to the best theoretical SM value given in Eq. (3). In this way the theoretical value for the total cross section σ could be lowered down to 2.7 pb. More interestingly, we see that the limits on $\Delta\sigma_{\mathrm{exp}}$ in Eq. (4) allow values of the CP violation parameter $\hat{d}_t'$ up to $\hat{d}_t' \approx 1.2$ (at the 1 s.d. level) if $\hat{\mu}_t'$ has an appropriate size. Thus, large effects of CP violation due to $\hat{d}_t'$ are not excluded by the present information on σ.

Due to the folding with PDF's, differential cross sections get smoothened, but still reflect the characteristic features of the parton level distributions. In Figs. 4–6 we show the normalized differential cross section with respect to the angle ϑ, the emission angle of the t jet in the laboratory ($p\bar{p}$ c.m.) frame. We choose $\vartheta = 0$ to correspond to t-emission in the direction of flight of the incoming proton. In all three plots, the solid lines are the SM result (in LO). In Fig. 4 we compare this to the distributions obtained with chromoelectric moments $\hat{d}_t' = 0.2$, 0.4, 0.6, 0.8, while

Fig. 5 shows the effect of a chromomagnetic moment for the values $\hat{\mu}'_t = 0.2$, -0.2, -0.4, -0.6. In Fig. 6 we show the angular distributions if both anomalous couplings are nonzero, $(\hat{d}'_t/\hat{\mu}'_t) = (0.8/-0.4)$ and $(0.4/-0.8)$. These values are chosen such that the anomalous contribution $\Delta\sigma$ to the total rate would be undetectable (cf. Fig. 3). From Figs. 4–6 we infer that the anomalous couplings would have to be rather large in order to be visible with a limited statistics of $t\bar{t}$ pairs.

In Figs. 7–9 we plot the normalized double differential cross section with respect to rapidity y and transverse momentum p_T of the t jet, as a function of p_T for different values of y. Fig. 7 shows the influence of chromoelectric moments $\hat{d}'_t = 0.2$ and 0.4, Fig. 8 of chromomagnetic moments $\hat{\mu}'_t = 0.2$ and -0.2, compared to the SM result (solid line). In Fig. 9 we show the combined influence of chromoelectric and chromomagnetic moments, again for $(\hat{d}'_t/\hat{\mu}'_t) = (0.8/-0.4)$ and $(0.4/-0.8)$. Typically the presence of anomalous dipole moments enhances the production of $t\bar{t}$ pairs with high transverse momentum.

As general feature we observe that normalized differential cross sections are of course more sensitive to anomalous dipole moments than the total rate. For small dipole moments, however, measurable differences occur mainly in phase space regions where the contribution to the total cross section is small, i.e. for large $|\cos\vartheta|$ or large p_T. Only if the anomalous couplings take quite sizable values, one can expect clear signals. A shift of the maximum of the curves in Fig. 9 of ≈ 50 GeV in p_T when going from the SM to $(\hat{d}'_t/\hat{\mu}'_t) = (0.8/-0.4)$ or $(0.4/-0.8)$ should clearly be detectable. By a detailed investigation of the $\cos\vartheta$ and y-p_T distributions we found that they are mainly influenced by the chromomagnetic moment $\hat{\mu}'_t$. For fixed $\hat{\mu}'_t$ we found only little dependence on $\hat{d}'_t$ when varying this quantity in the range allowed by the total cross section measurement (Fig. 3).

Finally we discuss the CP–odd observable $\hat{O}_L$ studied in [12] which is directly sensitive to $\hat{d}'_t$. The observable is constructed for the production and decay sequence

$$\begin{aligned} p + \bar{p} &\longrightarrow t + \bar{t} + X \;, \\ t &\longrightarrow W^+ + b \longrightarrow \ell^+ + \nu_\ell + b \;, \\ \bar{t} &\longrightarrow W^- + \bar{b} \longrightarrow \ell^- + \bar{\nu}_\ell + \bar{b} \;, \end{aligned} \tag{20}$$

where $\ell = e, \mu, \tau$. Let $\mathbf{p}$ ($\mathbf{q}_+, \mathbf{q}_-$) be the momentum of the proton (ℓ^+, ℓ^-) in the $p\bar{p}$ c.m. system. Then

$$\hat{O}_L = \frac{1}{m_t^3 |\mathbf{p}|^2}\, \mathbf{p}\cdot(\mathbf{q}_+ \times \mathbf{q}_-)\, \mathbf{p}\cdot(\mathbf{q}_+ - \mathbf{q}_-) \;. \tag{21}$$

This is an observable of the tensor type T_{ij} introduced in [32] and used in search for CP violation in the decay $Z \to \tau^+\tau^-$ [33]. In [12] the expectation value of $\hat{O}_L$ was calculated for $m_t = 130$ GeV keeping only terms of zeroth and first order in $\hat{d}'_t$ and setting $\hat{\mu}'_t = 0$. The result was

$$\langle \hat{O}_L \rangle = -0.012 \hat{d}'_t \;. \tag{22}$$

The number of events (Eq. (20)) needed to see a 1 s.d. effect can be estimated as (cf. Eq. (3.2) of [12])

$$N \simeq \frac{50}{|\hat{d}_t'|^2} \ . \tag{23}$$

If we take these numbers as an indication of the sensitivity of $\hat{O}_L$ to $\hat{d}_t'$ also for the top mass $m_t = 175$ GeV we can conclude that a few thousand events of the type Eq. (20) will be needed to see an effect of $|\hat{d}_t'| = 0.1$ at the 1 s.d. level by a measurement of $\langle \hat{O}_L \rangle$. A calculation of $\langle \hat{O}_L \rangle$ and of the expectation values of other CP–odd observables for $m_t = 175$ GeV and including the effects of $\hat{d}_t'$ and $\hat{\mu}_t'$ to all orders is in progress.

4 Conclusions

In this paper we have investigated the combined effects of a chromoelectric and chromomagnetic dipole moment of the top quark on the reaction $p\bar{p} \to t\bar{t}X$. We have calculated the matrix elements for the parton subprocesses $q\bar{q} \to t\bar{t}$ and $GG \to t\bar{t}$ in leading order QCD. The numerical evaluation of total and differential cross sections was done for Tevatron energies.

Our main findings can be summarized as follows:

(1) In the total cross section, a combination of chromoelectric and chromomagnetic dipole moments can yield a positive, negative or zero contribution. The total rate allows substantial values for the dipole moments: $\hat{d}_t'$, $\hat{\mu}_t'$ of order 1.

(2) Differential distributions can discriminate between chromoelectric and chromomagnetic dipole moments. However, since the main effect of the anomalous couplings is to change the absolute rate, normalized differential cross sections are sensitive only to quite sizable values of the couplings.

The most promising way to disentangle the dipole moments is to exploit their different transformation behaviour under CP. Since a chromoelectric (chromomagnetic) dipole moment is odd (even) under CP, one can construct CP–odd observables which are then sensitive to the chromoelectric moment $\hat{d}_t'$ only. A further advantage is that a CP–odd observable has already a linear dependence on $\hat{d}_t'$, whereas in cross sections $\hat{d}_t'$ can occur only with even powers. The CP–odd observable $\hat{O}_L$, Eq. (21), should be suitable for such an investigation.

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Appendix A

In this Appendix we derive the total parton level cross sections $\hat{\sigma}_{a\bar{a}}$, $a = q, G$. With

$$\hat{t} = m_t^2 - \frac{\hat{s}}{2}(1 - r\cos\hat{\vartheta}) \;, \qquad v = -\left(\frac{\hat{t}}{\hat{s}} - z\right)\left(1 + \frac{\hat{t}}{\hat{s}} - z\right) \tag{A.1}$$

we have

$$\hat{\sigma}_{a\bar{a}} = \int_{-1}^{1} d\cos\hat{\vartheta}\frac{d\hat{\sigma}_{a\bar{a}}}{d\cos\hat{\vartheta}} = \int_{\hat{t}_{\min}}^{\hat{t}_{\max}} d\hat{t}\;\frac{d\hat{\sigma}_{a\bar{a}}}{d\hat{t}}(z, v(\hat{t})) \;, \tag{A.2}$$

with $\hat{t}_{\min/\max} = m_t^2 - \frac{\hat{s}}{2}(1 \pm r)$. One can therefore translate the integration to the simple substitution rules

$$\hat{\sigma}_{a\bar{a}} \;=\; r\hat{s}\;\frac{d\hat{\sigma}_{a\bar{a}}}{d\hat{t}}\begin{pmatrix} v & \to & (1+2z)/6 \\ v^{-1} & \to & 2L \\ v^{-2} & \to & 2\left(z^{-1}+2L\right) \end{pmatrix} \;, \qquad L = \frac{1}{r}\ln\left(\frac{1+r}{1-r}\right) \;. \tag{A.3}$$

These rules can be applied directly to the differential cross sections $d\hat{\sigma}_{a\bar{a}}/d\hat{t}$ of Eqs. (11), (14), leading to the result

$$\hat{\sigma}_{q\bar{q}} = \frac{\pi\alpha_s^2}{\hat{s}}\frac{8r}{27}\left(1 + 2z + 6\hat{\mu}_t' + 2(2\hat{\mu}_t'^2 - \hat{d}_t'^2) + \frac{1}{2z}(\hat{\mu}_t'^2 + \hat{d}_t'^2)\right) \;, \tag{A.4}$$

$$\begin{aligned}\hat{\sigma}_{GG} = \frac{\pi\alpha_s^2}{\hat{s}}\frac{r}{12}\Bigg[&-7 - 31z + 4L\left(1 + 4z + z^2\right) \\ &+2\hat{\mu}_t'(\hat{\mu}_t' + 1)\left(-9 + 8L\right) + \left(\hat{\mu}_t'^2 + \hat{d}_t'^2\right)\left(\frac{7}{z}(1 + 2\hat{\mu}_t') + L(1 - 5\hat{\mu}_t')\right) \\ &+ (\hat{\mu}_t'^2 + \hat{d}_t'^2)^2\left(\frac{1}{3z}\left(1 + \frac{2}{z}\right) + 2L\right)\Bigg] \;.\end{aligned} \tag{A.5}$$

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Figure Captions

Figure 1: Vertex factors following from the top–gluon interaction Lagrangian in Eq. (7). All momenta are taken to be ingoing. The necessity of the second coupling is a consequence of gauge invariance.

Figure 2: Feynman diagrams for the quark annihilation $q\bar{q} \to t\bar{t}$ (a) and the gluon fusion $GG \to t\bar{t}$ (b–e) processes.

Figure 3: Contour plot of the anomalous contribution $\Delta\sigma$ defined in Eq. (6) as function of the chromoelectric and chromomagnetic dipole moments $\hat{d}'_t$ and $\hat{\mu}'_t$ (cf. Eq. (8)). The solid line corresponds to the mean experimental value $\Delta\sigma = 1.8$ pb (cf. Eq. (4)). The dashed lines enclose the experimentally allowed region (1 s.d.): -0.6 pb $\leq \Delta\sigma \leq 4.7$ pb. The dotted line corresponds to the SM result $\Delta\sigma = 0$.

Figure 4: Normalized differential cross section $(1/\sigma)(d\sigma/d\cos\vartheta)$ for $p\bar{p} \to t\bar{t}X$, where ϑ is the angle of the t jet in the $p\bar{p}$ c.m. frame. The solid line represents the LO SM result. The long-dashed (short-dashed, dot-dashed, dotted) line shows the effect of a chromoelectric dipole moment $\hat{d}'_t = 0.2$ (0.4, 0.6, 0.8) with $\hat{\mu}'_t = 0$.

Figure 5: Same as Fig. 4, now for different values of the chromomagnetic dipole moment. The long-dashed (short-dashed, dot-dashed, dotted) line corresponds to $\hat{\mu}'_t = 0.2$ (-0.2, -0.4, -0.6) with $\hat{d}'_t = 0$.

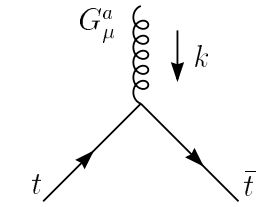
Figure 6: Same as Fig. 4, with nonzero values for both anomalous dipole moments. The dashed line shows the effect of $(\hat{d}'_t/\hat{\mu}'_t) = (0.8/-0.4)$, the dotted line is obtained from $(\hat{d}'_t/\hat{\mu}'_t) = (0.4/-0.8)$.

Figure 7: Normalized double differential cross section $(1/\sigma)(d^2\sigma/dydp_T^2)$ for the reaction $p\bar{p} \to t\bar{t}X$ plotted versus p_T for different values of y. p_T and y are transverse momentum and rapidity of the t jet. Shown is the SM result (solid line) and the distributions obtained with an anomalous chromoelectric moment $\hat{d}'_t = 0.2$ (dashed) and $\hat{d}'_t = 0.4$ (dotted) for $\hat{\mu}'_t = 0$.

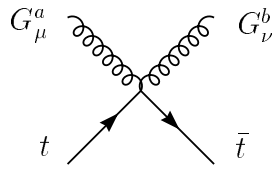
Figure 8: Same as Fig. 7, now for chromomagnetic dipole moments $\hat{\mu}'_t = 0.2$ (dashed) and $\hat{\mu}'_t = -0.2$ (dotted) for $\hat{d}'_t = 0$.

Figure 9: Same as Fig. 7, now with both $\hat{d}'_t$ and $\hat{\mu}'_t$ nonvanishing. The dashed line corresponds to $(\hat{d}'_t/\hat{\mu}'_t) = (0.8/-0.4)$, the dotted line to $(0.4/-0.8)$.

Figure 1



$$-ig_s\frac{\lambda^a}{2}\left[\gamma^\mu + i\frac{\hat{\mu}'_t}{m_t}\sigma^{\mu\nu}k_\nu - \frac{\hat{d}'_t}{m_t}\sigma^{\mu\nu}\gamma_5 k_\nu\right]$$



$$g_s^2 f_{abc}\frac{\lambda^c}{2}\left[i\frac{\hat{\mu}'_t}{m_t}\sigma^{\mu\nu} - \frac{\hat{d}'_t}{m_t}\sigma^{\mu\nu}\gamma_5\right]$$

Figure 2

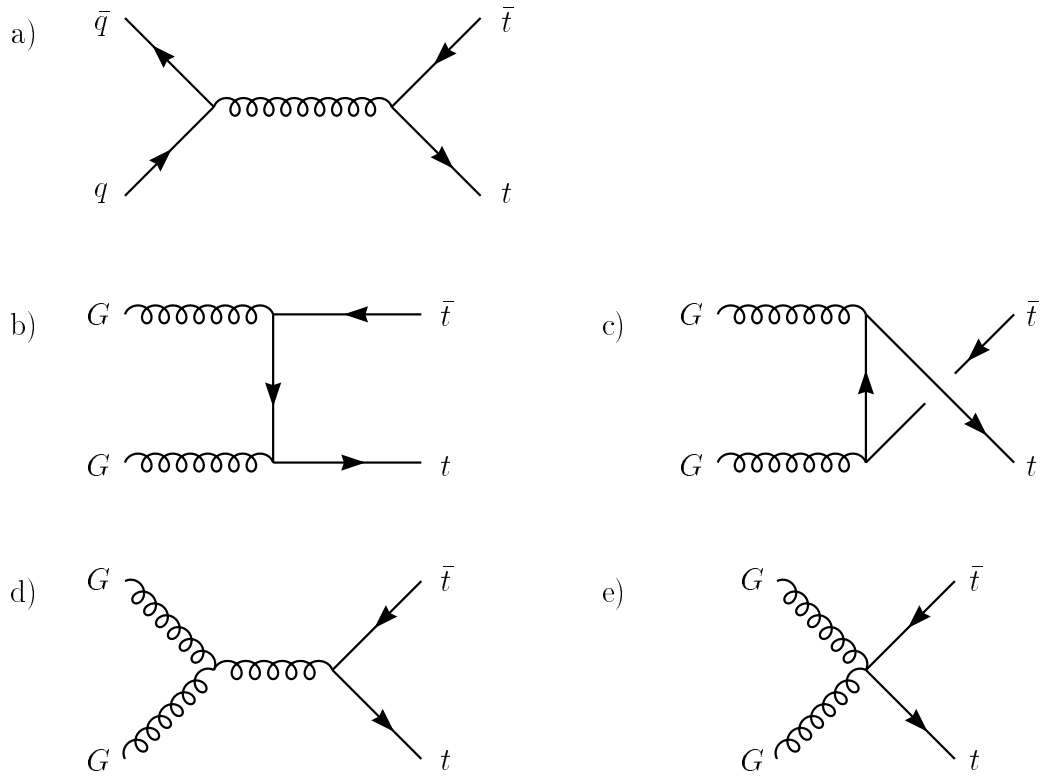


Figure 3

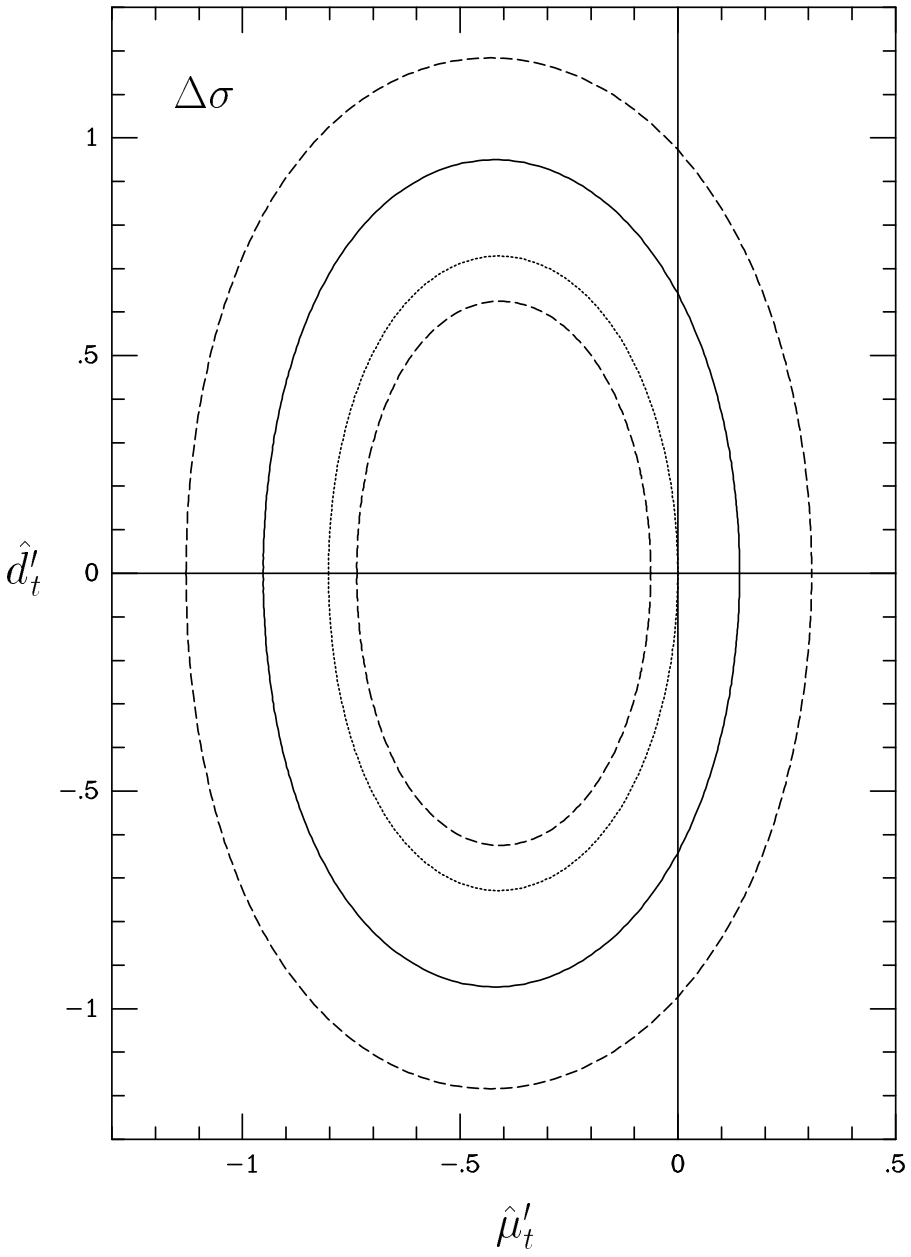


Figure 4

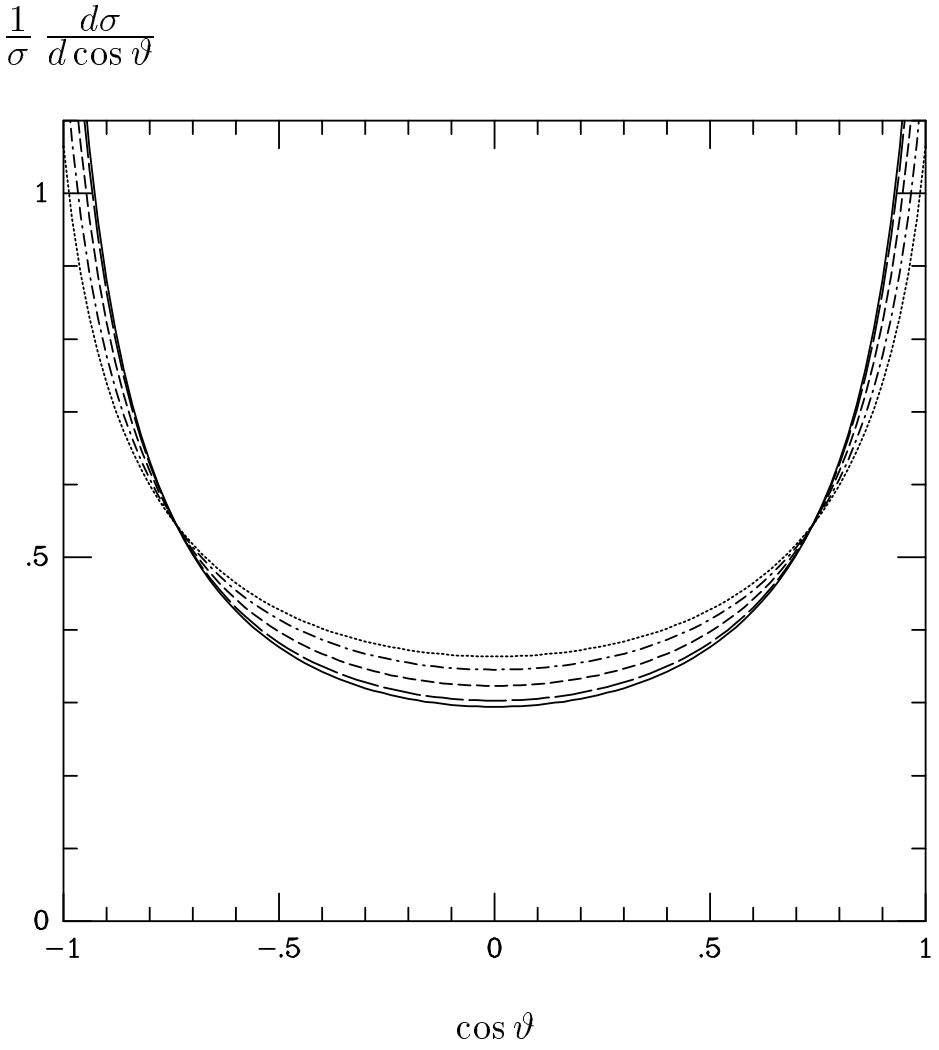

$\frac{1}{\sigma}\,\frac{d\sigma}{d\cos\vartheta}$
1
.5
0
−1
−.5
0
.5
1
$\cos\vartheta$

Figure 5

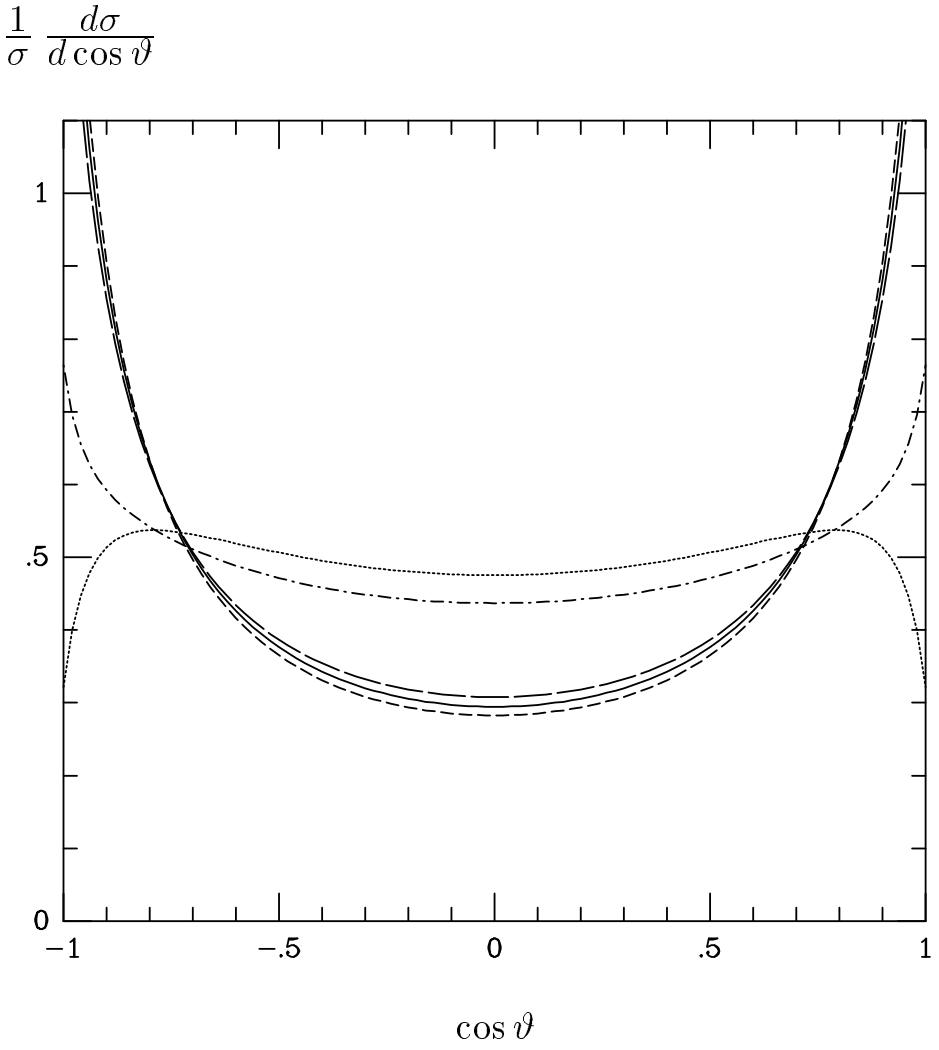

$\frac{1}{\sigma}\,\frac{d\sigma}{d\cos\vartheta}$
1
.5
0
−1
−.5
0
.5
1
$\cos\vartheta$

Figure 6

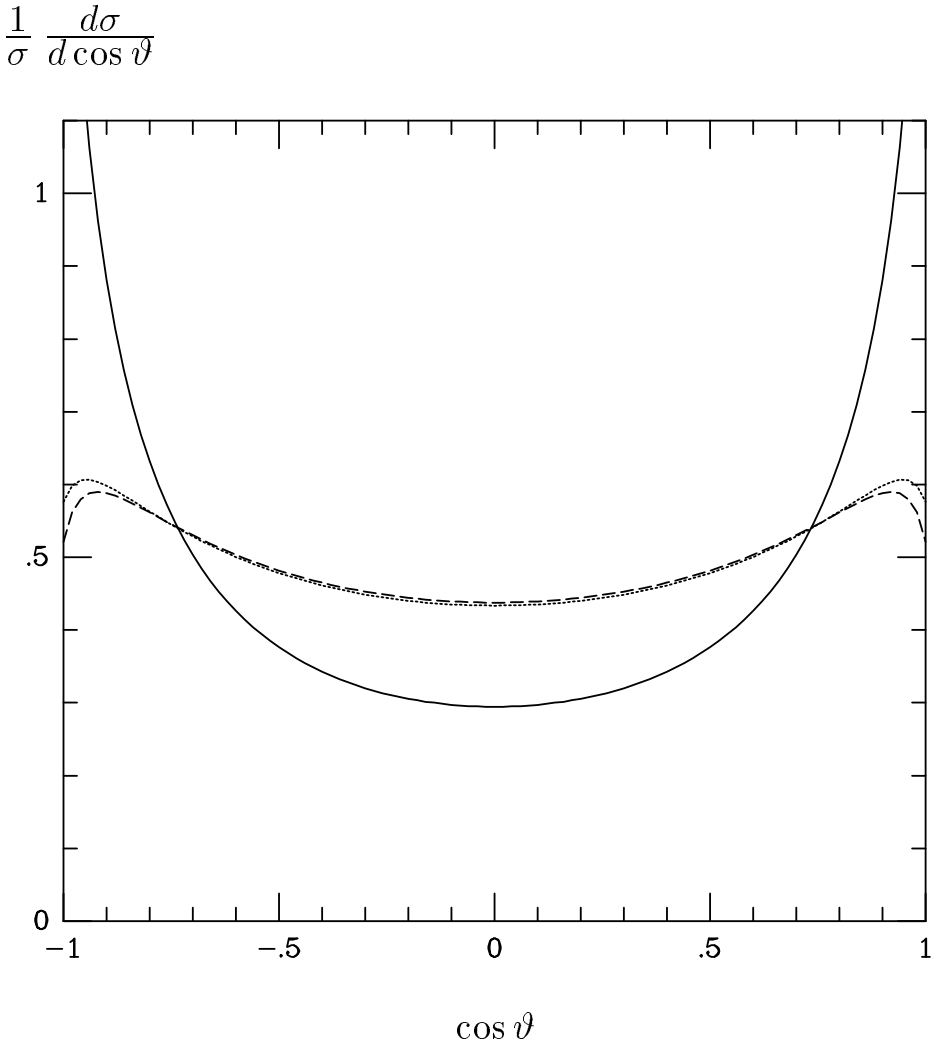

$\frac{1}{\sigma}\,\frac{d\sigma}{d\cos\vartheta}$
1
.5
0
−1
−.5
0
.5
1
$\cos\vartheta$

Figure 7

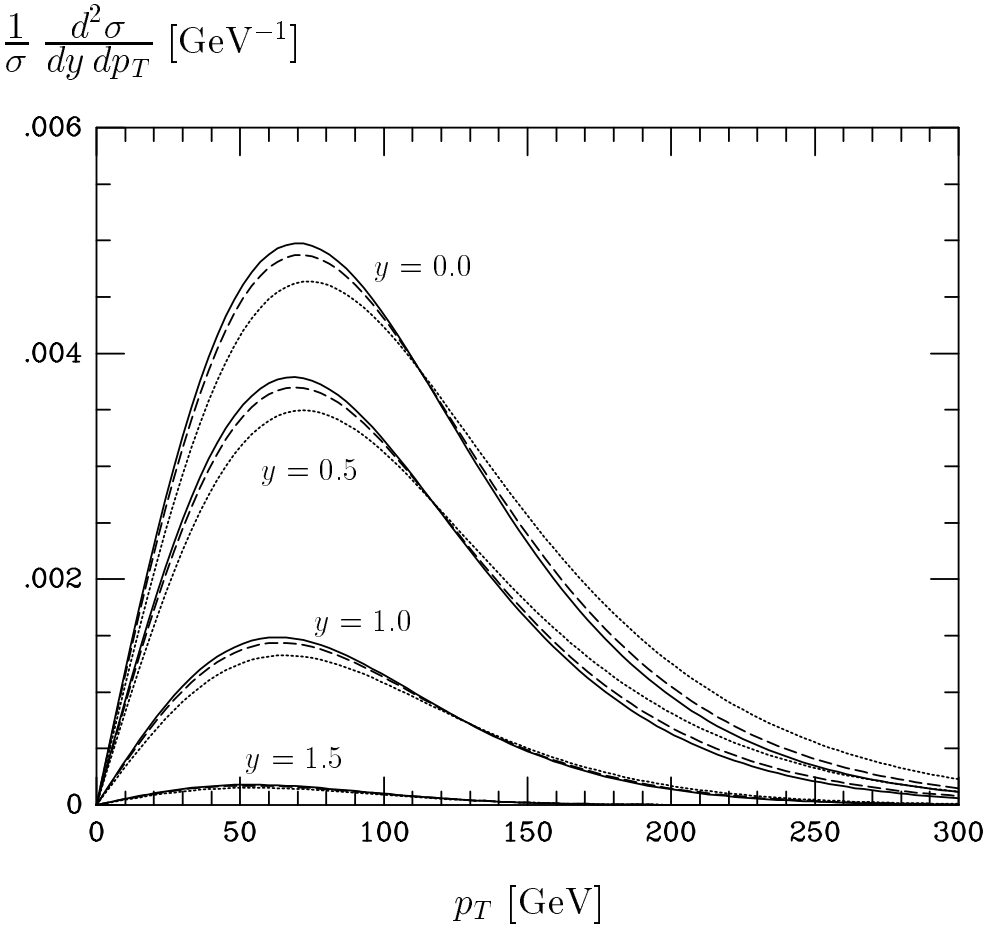

$\frac{1}{\sigma}\,\frac{d^2\sigma}{dy\,dp_T}$ [GeV^{-1}]
.006
.004
.002
0
$y = 0.0$
$y = 0.5$
$y = 1.0$
$y = 1.5$
0
50
100
150
200
250
300
p_T [GeV]

Figure 8

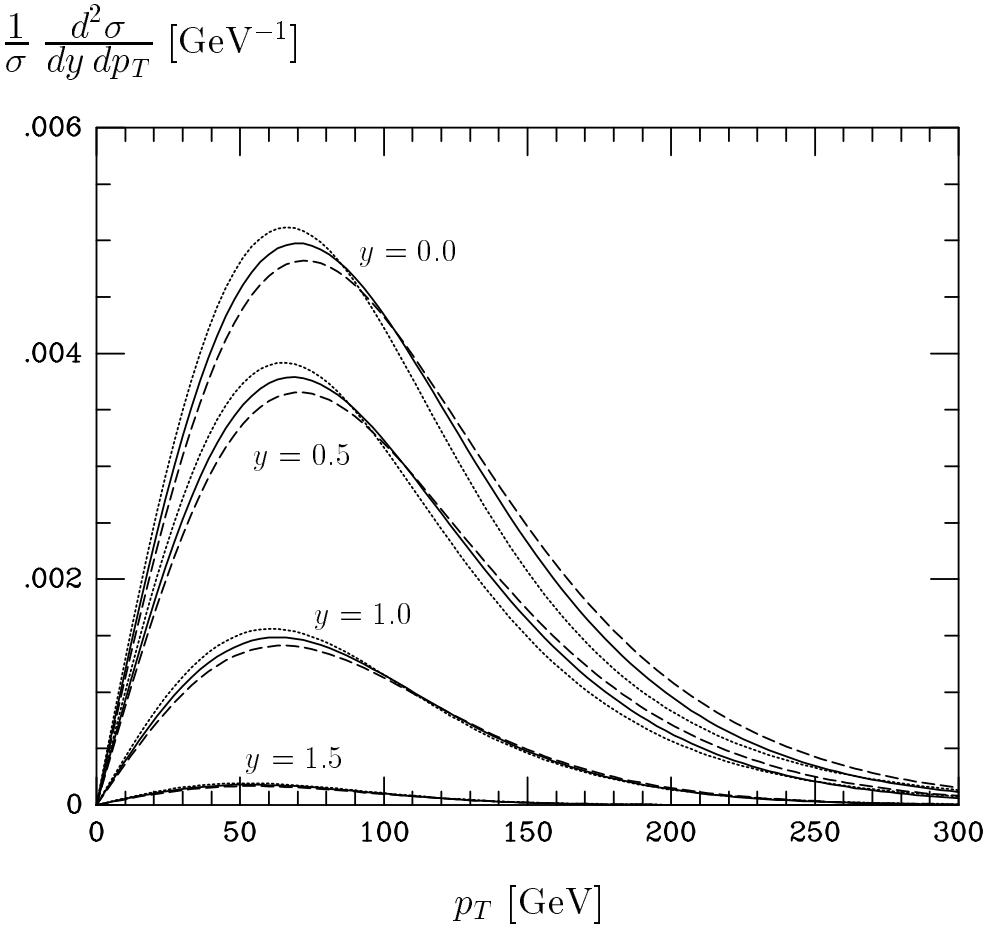
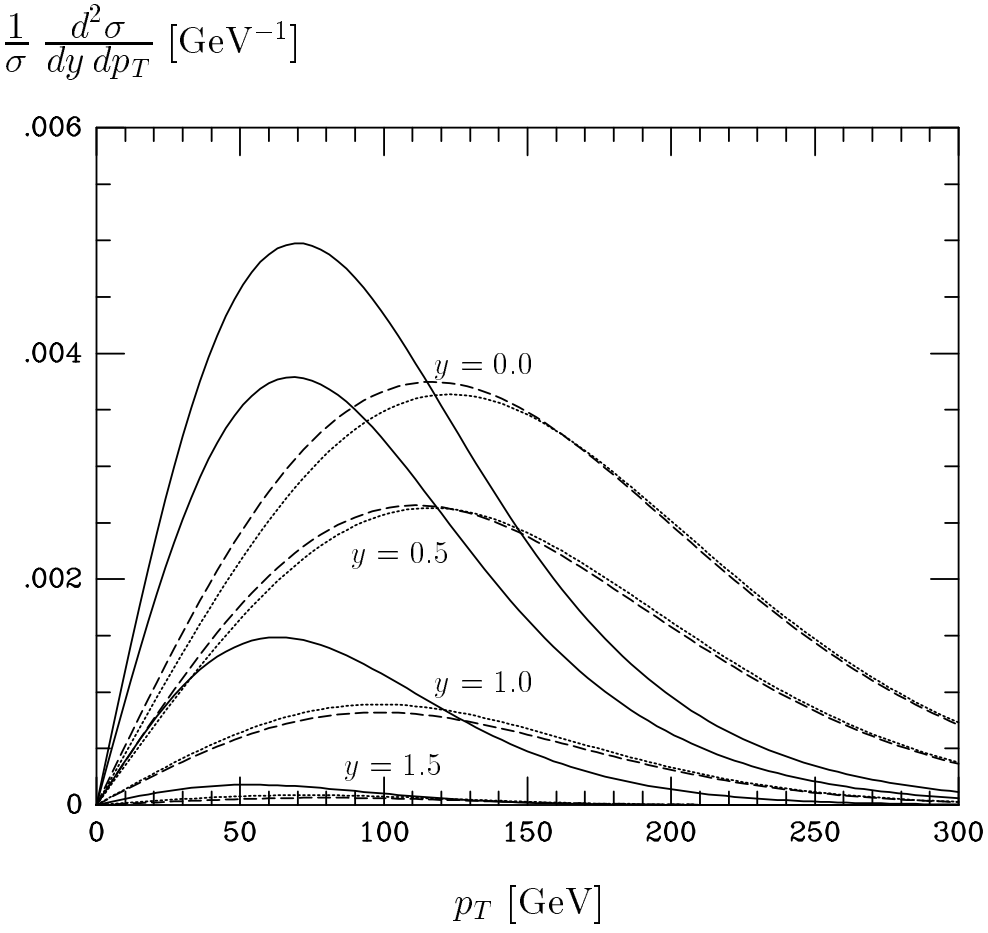

$\frac{1}{\sigma}\,\frac{d^2\sigma}{dy\,dp_T}\ [\mathrm{GeV}^{-1}]$
.006
.004
.002
0
$y = 0.0$
$y = 0.5$
$y = 1.0$
$y = 1.5$
0
50
100
150
200
250
300
p_T [GeV]

Figure 9


$\frac{1}{\sigma}\,\frac{d^2\sigma}{dy\,dp_T}$ [GeV^{-1}]
.006
.004
.002
0
0
50
100
150
200
250
300
$y = 0.0$
$y = 0.5$
$y = 1.0$
$y = 1.5$
p_T [GeV]